ACCIDENT RISKS IN THE ENERGY SECTOR: COMPARATIVE EVALUATIONS

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Severe accidents are considered one of the most controversial issues in current comparative studies of the environmental and health impact of energy systems. The present work focuses on severe accident scenarios relating to fossil energy chains (coal, oil and gas), nuclear power and hydro-power. The scope of the study is not limited to the power production (conversion) step of these energy chains, but, wherever applicable, also includes full energy chains. With the exception of the nuclear chain, the focus of the present work is on the evaluation of the historical experience of accidents. The basis for this evaluation is the comprehensive database ENSAD (Energy-Related Severe Accident Database), which has been established at PSI. For hypothetical nuclear accidents, a probabilistic technique has also been employed. The broader picture, derived from examination of full energy chains, leads, on a world-wide basis, to the conclusion that immediate fatality rates are much higher for the fossil chains than expected if only power plants are considered. Generally, immediate fatality rates are significantly higher for non-OECD countries than for OECD countries, and, in the case of hydro and nuclear, the difference is rather dramatic. In addition to aggregated values, frequency-consequence curves are also provided, since they not only reflect implicitly a ranking based on aggregated values, but also include such information as the observed, or predicted, chain-specific maximum extent of damages. Finally, damage and external costs of severe accidents for the different energy chains have been estimated, based on the unit cost values for the various consequence types.

1 INTRODUCTION

Severe accidents in the energy sector have been identified as one of the main contributors to man-made disasters. In 1998, ENSAD (Energy-Related Severe Accident Database), a highly comprehensive database of severe accidents, with emphasis in the energy sector, was established at PSI. The historical experience represented in this database has been supplemented by probabilistic analyses for nuclear energy in order to carry out a detailed comparison of severe accident risks in the broader energy sector [1]. The database enables comprehensive analyses of accident risks to be performed. The analyses are not limited to power plants, but cover full energy chains, including exploration, extraction, processing, storage, transport and waste management.

The ENSAD database, and the associated analyses, have now been much extended, not only in terms of the data as such, but also in terms of the scope of applications. This work has been mainly undertaken within the NewExt EC DG Research Project on *New Elements for the Assessment of External Costs from Energy Technologies*, which, apart from the issue of accidents within non-nuclear energy chains [2,3], has also addressed other unresolved issues in the context of energy externalities.

The main objectives of the present work are: (a) to carry out a comparative assessment of severe accidents in the energy sector, and (b) to assess the external costs associated with severe accidents within the various energy chains. Thus, the results can both support policy decisions and serve as an essential input to the evaluation of the sustainability of specific energy systems. Earlier studies had already identified the lack of estimates of external costs of non-nuclear accidents to be one of the major limitations of the state-of-the-art of externality assessment.

2 OVERVIEW AND STATUS OF ENSAD

2.1 Database extensions

The extensions of the ENSAD database, and the scope of the analyses, have taken place on various levels.

- Information from a variety of commercial and non-commercial data sources, not considered earlier, has now been added. Examples include specialized databases, covering oil spills and accidents involving dams.

- The time period covered has been extended to reflect historical experience up to the year 2000: previously, only data up to 1996 were included.

- Apart from severe accidents, small accidents have also been addressed. These accidents were, however, investigated at a lower level of detail.

- Because of PSI's involvement in the *China Energy Technology Program of the Alliance for Global Sustainability*, it has been possible to gain access to previously restricted information on accidents in China [4,5]; previously, records on such accidents were almost impossible to acquire.

- Within the externality assessment, valuation of the relevant endpoints (such as death and injury, evacuation of population, costs of oil spills, etc.) was carried out, and the degree of internalization was addressed.

2.2 Severe accident definition

Based on the available literature, there is no unique definition of a severe accident as such. All definitions include various consequence, or damage, types (fatalities, injured persons, evacuees, or costs), and a minimum level for each damage type. The differences between the various definitions relate to both the set of specific consequence types considered, and the damage thresholds.

This can be illustrated by the following examples. The 'World-Wide Offshore Accident Database' (WOAD) of the Det Norske Veritas (DNV) considers an accident to be severe, or major, if more than one fatality occurs, or if the damaged unit (e.g. oil platform, drill ship or drill barge) experiences total loss [6]. Glickman & Terry [7] define a "significant accident" for technological hazards to be one which resulted in at least five fatalities, or if it involved the release of a chemical, petroleum product, hazardous waste, or other hazardous material. Neither the SIGMA publication series of the Swiss Re Company [8], nor Rowe [9], explicitly use the term "severe accidents". However, they do investigate, and collect data on, catastrophic events.

Within the framework of the database ENSAD at PSI, an accident is considered to be *severe* if it is characterized by one or more of the following consequences:

1) at least five fatalities;

2) at least ten injuries;

3) at least 200 evacuees;

4) the imposition of an extensive ban on consumption of food;

5) releases of hydrocarbons exceeding 10 000 t;

6) enforced clean-up of land and water over an area of at least 25 km^2;

7) economic loss of at least five million USD (2000).

Analyses presented in this paper focus on those accidents which resulted in at least five fatalities; the completeness and accuracy of data concerning fatalities is superior to coverage of other types of consequences [1,2].

2.3 Overview of historical experience

2.3.1 Distribution of severe accidents by various categories

The ENSAD database currently contains information on 18 400 accidents. Man-made accidents comprise 12 943 (or 70.3%) of the total, whereas natural disasters account for the remaining 5457. Of the 6404 energy-related accidents (corresponding to 34.8% of all accidents, or 49.5% of man-made accidents), 3117 (48.7%) are classified as severe, of which 2078 have five or more fatalities. Non-energy-related accidents and natural disasters are of second priority within ENSAD. Consequently, the corresponding data are likely to be less complete, and of lower quality, than those provided for the energy-related accidents.

About 89% of all accidents contained in ENSAD occurred in the time period 1969 to 2000. This concentration is mainly due to the larger volume of activities, although improved reporting of accidents is also likely to have played an important part. Figure 1 shows the number of fatalities worldwide for different types of accidents for this period of more than 30 years.
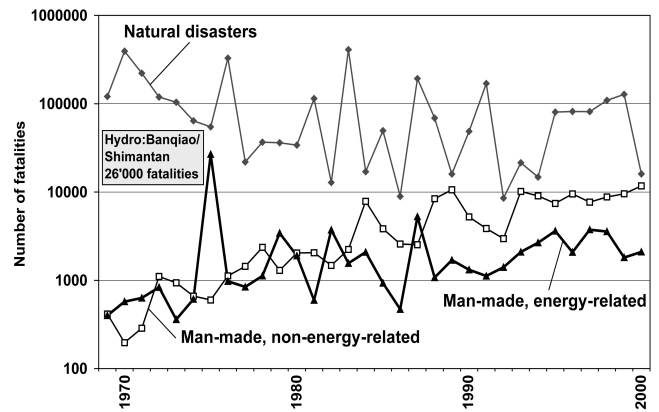
Fig. 1: Number of fatalities for severe (≥ 5 fatalities) accidents that occurred due to natural disasters and man-made accidents in the period 1969 to 2000; based on data from [2].

2.3.2 Severe energy-related accidents worldwide

For the various energy chains, the ENSAD database at PSI includes 1860 accidents (amounting to 81 258 fatalities) classified as severe, because five or more fatalities occurred (Table 1). The coal chain accounted for about 65.6% of all accidents, followed (a long way behind) by oil, with 21.3%. Contributions due to natural gas (6.7%) and LPG (5.6%) were much smaller, while both hydro and nuclear account for less than 1% each. This dominance of coal-chain accidents is fully attributable to the release of detailed accident statistics by China's coal industry, data that were not publicly available before [4,5]. Altogether, 819 of the 1044 accidents collected for the Chinese coal chain occurred in the years 1994-1999, implying substantial under-reporting prior to the release of the annual editions of the China Coal Industry Yearbook.

Table 1: Summary of severe accidents that occurred in the various energy chains of the OECD and non-OECD countries from 1969 to 2000. Accidents resulting in the largest numbers of fatalities are also given; data from [2].

| Energy chain	OECD			non-OECD		
	Accidents	Fatalities	Accident with max fatalities	Accidents	Fatalities	Accident with max fatalities
Coal	75	2259	272	102 1044 [1]	4831 18'017 [1]	434 284 [1]
Oil	165	3789	577	232	16'494	4375
Natural Gas	80	978	109	45	1000	100
LPG	59	1905	498	46	2016	600
Hydro	1	14	14	10	29'924 [2]	26'000
Nuclear [3]	--	--	--	1	31	31

[1] First line: Coal non-OECD w/o China; second line: Coal China.
[2] Banqiao/Shimantan dam failures alone caused 26 000 fatalities.
[3] Latent fatalities are treated separately.

The types of fatality were clearly dominated by the Banqiao/Shimantan dam failures, which together resulted in 26 000 deaths. As a consequence, the hydro chain accounts for 36.8% of all fatalities. Among the fossil chains, coal remained most accident-prone, followed by oil, LPG and natural gas.

On average, for the period 1969 to 2000, 58 severe accidents occurred each year worldwide (Fig. 2a). About 60% of all accidents happened during the period 1993 to 2000. This dominance is primarily due to improved reporting of coal accidents in China, and their publication in the China Coal Industry Yearbook (CCIY). Considering different gravity indices for fatalities, over 72% of all accidents resulted in 5-20 fatalities, whereas accidents exceeding 100 fatalities ranged from 0 to 5 per year.
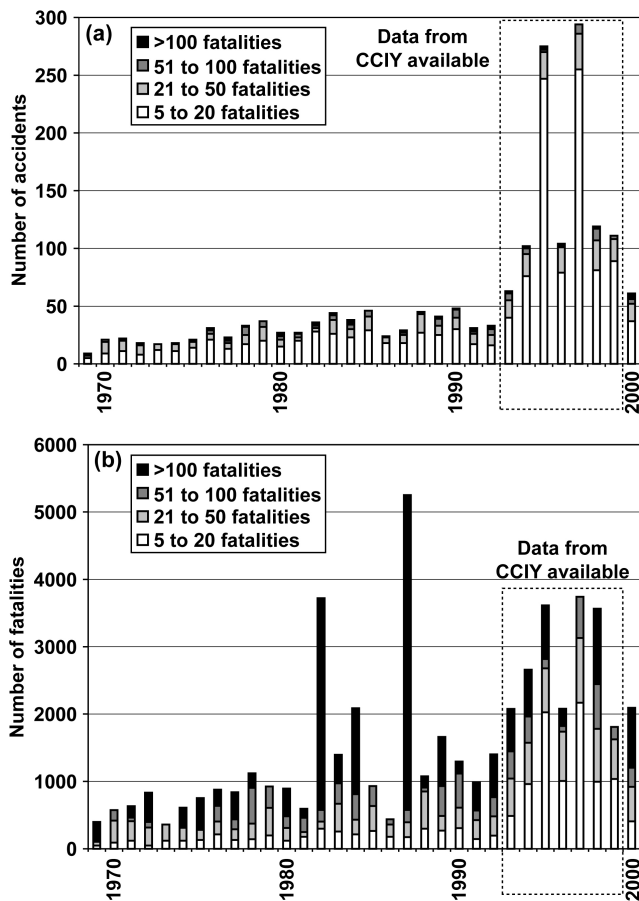
Fig. 2: Worldwide numbers of (a) severe accidents, and (b) fatalities, in the various energy chains, according to different gravity indices, for the period 1969 to 2000; the box indicates the period for which data from the China Coal Industry Yearbook (CCIY) are available. Data from the Banqiao/Shimantan dam failures (with 26 000 fatalities) are not shown in Fig. 2b. Based on data from [2].

In total, the average number of fatalities was 2539 per year, but this number would drop to about 1727 if the largest accident (the Banqiao/Shimantan dam failure, with 26 000 fatalities) were excluded (Fig. 2b). Similarly, the peaks which occur for the years 1982 and 1987 are strongly influenced by two very large

accidents in the oil sector in Afghanistan (2700 fatalities) and the Philippines (4375 fatalities), which make up 73% and 83% of all fatalities, respectively, for these years. In contrast, the fatality peaks for 1995 and 1997 are primarily due to accidents in the size categories "5-20 fatalities" and "21-50 fatalities" in the Chinese coal chain (Figs. 2a, 2b).

## 3 SELECTED CHAIN-SPECIFIC ANALYSES

Figure 3 shows the number of fatalities for severe accidents in the fossil energy chains, classified according to the different stages in the chain. Note that similar patterns were found for the number of severe accidents, which are not shown in the Figure.

For the coal chain, the majority of fatalities occurred at the *Extraction* stage (Fig. 3a). However, the share of accidents in the *Exploration* stage is very large in the Chinese coal chain, compared to the almost insignificant shares for the OECD and the other non-OECD countries. An evaluation of the causes for severe coal accidents revealed that explosions of methane gas in mines were the most frequent cause, ranging from 57% for the OECD countries to 80% for China (50% for other non-OECD countries). Fires, roof collapse and transport accidents generally had individual contributions below 7%. For additional information, we refer the reader to [1,2] or, in the specific case of the Chinese coal chain, to [4,5].

Transportation (i.e. *Regional Distribution* and *Transport to Refinery*) was the most accident-prone of the stages in the oil chain (Fig. 3b), accounting for 72.9% of fatalities in OECD countries and 89.9% in non-OECD countries. Deaths resulting from the *Refinery*, *Extraction* and *Exploration* stages were much less significant, and the contributions from the *Heating* and *Power Plant* stages were practically negligible. Analysis of transportation modes for the oil chain revealed that maritime accidents dominated within the *Transport to Refinery* stage. This was due primarily to tankers exploding, catching fire, running aground or being involved in maritime collisions. Concerning the *Regional Distribution* stage, road accidents were the most common, caused mainly by the overturning of road tankers, and their collisions with other vehicles.

For the natural gas chain, the majority of fatalities also occurred during transportation (OECD 78.0%; non-OECD 50.2%), followed by *Heating* (16.6% vs. 27.8%); details are given in Fig. 3c. Nearly 57% of all accidents occurred during transport via pipelines, followed, though distantly, by activities such as processing (10.4%), storage (8.8%), and incidents originating in domestic or commercial premises (17.6%). The majority of accidents involving pipelines were caused by impact failures (46%), and mechanical failures (30%).

Concerning the LPG chain, *Regional Distribution* accounted for 72.1% of fatalities in OECD countries, whereas the contribution due to *Long Distance Transport* was minimal (Fig. 3d).
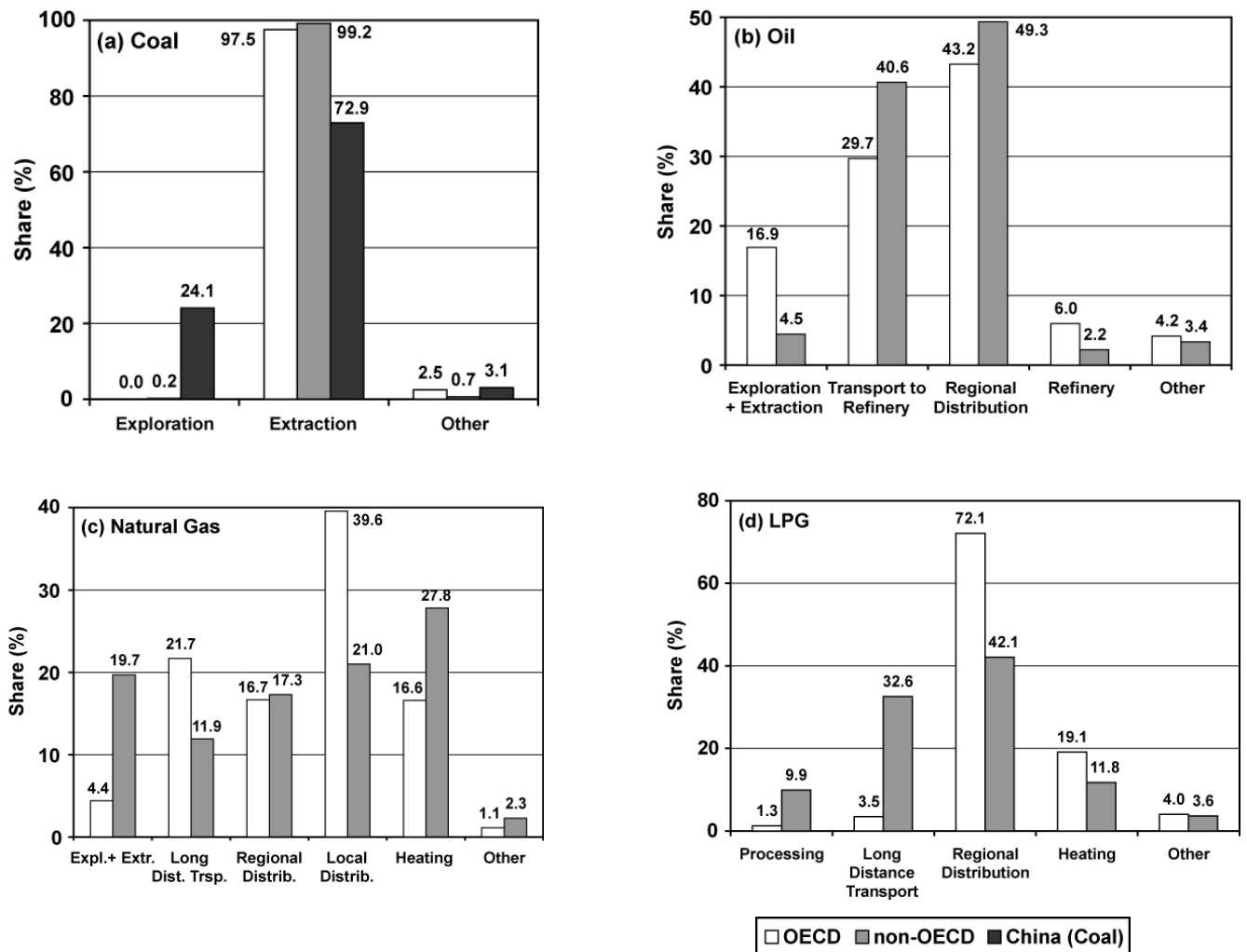
Fig. 3: Shares of fatalities in severe accidents, according to the stages in the energy chain. Data are shown for both OECD and non-OECD countries. For the coal chain, results for China, and other non-OECD countries, are shown separately; data from [2].

In non-OECD countries, *Regional Distribution* (42.1%) and *Long Distance Transport* (32.6%) made up about 75% of all fatalities. The distinctly higher percentage contribution of the *Long Distance Transport* stage in non-OECD countries was due to the largest recorded LPG accident, with 600 fatalities (Asha-Ufa, Russia), which alone amounted to 29.8% of all fatalities in this category.

Concerning accident causes related to the different activities, no detailed evaluation is possible, because most accident descriptions did not contain the relevant information. Consequently, only some broad trends can be identified, though ones which appear to be in accord with results from earlier studies [1]. Impact failures were the most important cause for accidents during transport, whereas mechanical failures were the most frequent cause for accidents during processing, transfer and storage activities.

## 4   DAMAGE INDICATORS AND FREQUENCY-CONSEQUENCE CURVES

Selected, aggregated accident indicators have been assembled and compared. The approach used considers contributions from all stages of the analyzed fuel cycles. The comparison of different energy chains is based on "normalized" indicators, i.e. those combining consequences (e.g. number of fatalities) and product (e.g. electricity generation), and on the estimated accident-related external costs for selected technologies. Figure 4 shows results in terms of affected people per GW_eyr, differentiating between OECD and non-OECD countries. It should be noted that the statistical bases for the indicators for the various energy chains may be radically different. For example, there are 1221 severe accidents with fatalities in the coal chain, and only one in the nuclear chain (Chernobyl).

The frequency-consequence curves for OECD and non-OECD countries are given in Fig. 5 and Fig. 6, respectively. Fossil energy chains in non-OECD countries are ranked similarly to those of the OECD countries, except for the Chinese coal chain, which exhibits significantly higher accident frequencies than in other non-OECD countries.
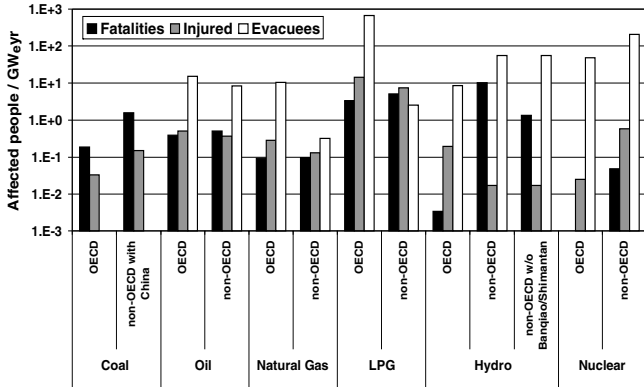

Fig. 4: Accumulated damage rates based on historical experience of severe accidents in OECD and non-OECD countries for the period 1969 to 2000. The indicators were estimated with partial reallocation of the damage to OECD countries due to import of fossil energy carriers from non-OECD countries. Only immediate fatalities are shown; latent fatalities are commented upon in the text. Based on data from [2].

However, the vast majority of severe coal accidents in China result in less than 100 fatalities per incident. Accident frequencies in the oil and hydro chains are also much lower than for the (Chinese) coal chain, but maximum numbers of fatalities are, respectively, one or two orders of magnitude higher than for the coal and natural gas chains.
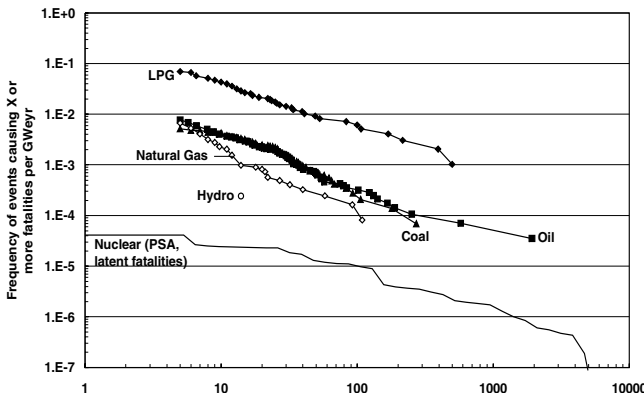
Fig. 5: Comparison of frequency-consequence curves for full energy chains in OECD countries, with partial reallocation, for the period 1969 to 2000. The curves for coal, oil, natural gas, LPG and hydro are based on historical accidents, and show immediate fatalities [2]. For the nuclear chain, the results originate from a plant-specific Probabilistic Safety Assessment (PSA), and reflect latent fatalities [1].

Expectation values for severe accident fatality rates associated with the nuclear chain differ markedly from the two cases shown in Figs. 5, 6. The maximum credible consequences of nuclear accidents may be very large in terms of latent fatalities, i.e. comparable to the number of immediate fatalities in the Banqiao/Shimantan dam accident, which occurred in China in 1975. However, the large differences between the Chernobyl-based historical estimates and earlier estimates, based on Probabilistic Safety Assessment (PSA) for the Swiss nuclear power plant Muehleberg [1], illustrate the limitations in the applicability of past accident data to cases that are radically different in terms of technology and operational environment. In this sense, the Chernobyl accident is, in fact, not representative of currently operating plants, including those in non-OECD countries.
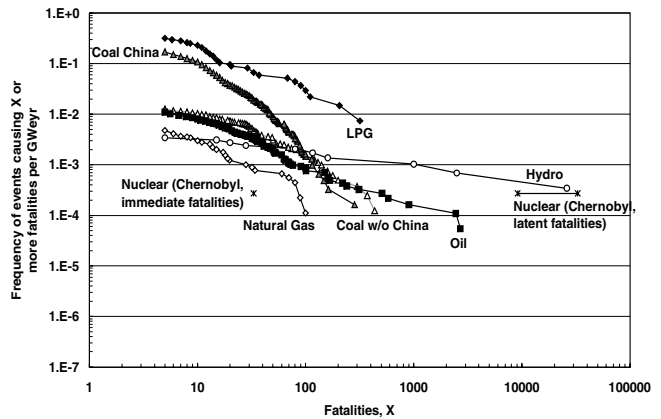
Fig. 6: Comparison of frequency-consequence curves for full energy chains in non-OECD countries with partial reallocation for the period 1969-2000. The curves for coal w/o China, coal with China, oil, natural gas, LPG and hydro are based on historical accidents, and show immediate fatalities [2]. For the nuclear chain, the immediate fatalities are represented by one point (Chernobyl). Lower and upper bounds are given for the estimated Chernobyl-specific latent fatalities [1].

5 DAMAGE COSTS AND EXTERNAL COSTS OF SEVERE ACCIDENTS

Damage costs and external costs of severe accidents in different energy chains have been estimated, based on unit-cost values for the various types of consequences. Table 2 gives results for the immediate fatalities, obtained using the historical experience available in both OECD and non-OECD countries. Since the costs provided in the table only cover immediate fatalities, it is of interest to relate them to the accident damage costs derived from a PSA of the nuclear power plant Muehleberg, which are dominated by the costs of latent fatalities. The mean value has been estimated at 1.2E-3 US-Ct./kWh$_e$, with 5th and 95th percentiles at 1.0E-4 and 3.8E-3 US-Ct./kWh$_e$; these results include damage costs of non-health effects [1].

The estimated costs of injuries and evacuations are based on less complete statistical data than those for fatalities, but are generally much less significant.

The central estimate of oil-spill-damage costs is 3.7E-3 EUR-Ct.(2002)/kWh$_e$ for the OECD countries and 5.5E-3 EUR-Ct.(2002)/kWh$_e$ for non-OECD countries, with maximum estimates one order of magnitude higher. Other types of economic damage due to accidents were also assessed, and expressed in terms of damage costs; these may be significant in some cases, but the basis is too heterogeneous to allow even a reasonably consistent comparison to be made.

Table 2: Summary of full-chain damage and external costs (EUR-Ct.(2002)/kWh) of severe accidents with at least five immediate fatalities; the reference coal, oil and natural-gas electricity-generating plants have efficiencies of 41%, 30% and 53%, respectively. (The mean value of a "Statistical Life" is estimated at 1.045 million EUR).

Energy chain	Reference countries	Damage costs in EUR-Ct.(2002)/kWh$_e$			External costs in EUR-Ct.(2002)/kWh$_e$		
		Occupational	Public	Total	Occupational	Public	Total
Coal	*OECD*	1.7E-3	1.2E-5	1.7E-3	3.4E-4	6.1E-6	3.5E-4
	non-OECD w/o China	6.5E-3	4.3E-5	6.5E-3	3.2E-3	3.5E-5	3.3E-3
	China (1994-1999)	1.2E-2	ng[3]	1.2E-2	6.1E-3	ng	6.1E-3
Oil	*OECD*	9.9E-4	9.0E-4	1.9E-3	2.0E-4	4.5E-4	6.5E-4
	non-OECD	1.8E-3	1.1E-2	1.3E-2	9.1E-4	8.7E-3	9.6E-3
Natural gas	*OECD*	2.2E-4	4.4E-4	6.6E-4	4.5E-5	2.2E-4	2.6E-4
	non-OECD	3.3E-4	5.9E-4	9.2E-4	1.6E-4	4.7E-4	6.3E-4
Hydro	*OECD*	ng	4.1E-5	4.1E-5	ng	2.0E-5	2.0E-5
	non-OECD	ng	1.2E-1	1.2E-1	ng	9.8E-2	9.8E-2
	non-OECD w/o Banqiao /Shimantan	ng	1.6E-2	1.6E-2	ng	1.3E-2	1.3E-2
Nuclear	*OECD[1]*	ng	ng	ng	ng	ng	ng
	non-OECD[2]	5.7E-4	ng	5.7E-4	2.9E-4	ng	2.9E-4

[1] Based on Probabilistic Safety Assessment (PSA).
[2] Based on the Chernobyl accident.
[3] ng = negligible.

6 CONCLUSIONS

6.1 Specific energy chains

The conclusions for the hydro and nuclear chains have already been documented [1], so we restrict ourselves here to the coal, oil, natural gas and LPG chains only.

Coal chain

- The overall number of severe accidents in the coal chain decreased slightly in OECD countries over the last two decades, but increased for the non-OECD countries.

- The Chinese coal chain is a special case, with more than 6000 fatalities (about one third due to severe accidents) every year, and a fatality rate about ten times higher than in other non-OECD countries, and about 40 times higher than in OECD countries (no allocation of damages).

- The stage in the coal chain with by far the most fatalities is *Extraction*; the other stages have relatively small contributions to severe accidents.

- Methane gas explosions in underground mines were the most frequent cause of severe coal accidents worldwide.

Oil chain

- Accompanying higher oil consumption, there has been a trend towards an increasing number of severe accidents (and resulting fatalities) in non-OECD countries, though not in OECD countries.

- The most risk-prone stages in the oil chain are *Regional Distribution* and *Transport to Refinery*.

- The most frequent accidents during the stage *Transport to Refinery* occur at sea, while the most frequent accidents during the stage *Regional Distribution* occur on the road.

Natural gas and LPG chains

- The annual number of severe accidents in the LPG and natural gas chains increased significantly after 1970 in non-OECD countries, whereas OECD countries showed the opposite trend. However, there is a large scatter in the number of accidents from year to year.

- The majority of severe accidents occurred in the stages *Long Distance Transport*, *Regional Distribution*, *Local Distribution* and *Heating* for natural gas, and *Regional Distribution* for LPG.

- Nearly 60% of all severe natural gas accidents occurred during transport via pipelines.

- Almost half of all severe LPG accidents occurred during transport, particularly by road tankers. The dominant accident cause was collision.

6.2 Comparative aspects

- Comprehensive historical evidence of energy-related severe accidents is available, and can be used as a basis for quantifying the corresponding damages and external costs. Small accidents are strongly under-reported, but their contribution to external costs appears anyway to be quite small.

- Energy-related accident risks in non-OECD countries are distinctly higher than in OECD countries.

- Hydropower in non-OECD countries, and the upstream stages within the fossil energy chains, are the most accident-prone industries.

- Estimated fatality rates are lowest for western hydropower and nuclear power plants. This results in low associated external costs. However, the maximum credible consequences are very large. The corresponding risk valuation is subject to stakeholder value judgments, and can be pursued using multi-criteria decision analysis.

- The damage caused by severe accidents in the energy sector is substantial, but quite small compared to those caused by natural disasters. External costs associated with severe accidents are rather insignificant compared with the external costs of air pollution.

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